6.x Optical impairments in Access Networks

Any optical access system has to have a useful tolerance to unwanted optical effects. Some of the effects are intrinsic linear (e.g., loss, dispersion, Rayleigh) or nonlinear (e.g., Raman, Brillouin, and Self-phase modulation) characteristics of the fiber. Some are caused by imperfections of the construction of the ODN and equipment (e.g., reflections, filter isolation), and some are caused by the interaction of the multiple channels (if present) in the fiber and in the detectors. This section will give a brief inventory of these effects, to help guide the preparation of the technical analysis of the candidate systems.

6.x.1. Intrinsic fiber effects

The fiber presents several intrinsic impairments. The primary linear effects are loss, dispersion, and Rayleigh back-scattering. The loss is caused by material absorption and scattering, and causes the simple reduction in signal power. The dispersion is caused by the combination of material index variation and waveguide velocity as a function of the signal wavelength. Dispersion causes pulses to spread and generates inter-symbol interference. It also can have beneficial effects in that co-propagating waves will suffer phase walk-off with dispersion, and this can reduce other coherent effects. Rayleigh scattering is caused by the microscopic variations of the density of the glass, some of the scatter travels backwards in the fiber. This acts as a distributed reflection. The impact of reflections is discussed below.

The primary nonlinear effects are Brillouin, Raman, and self- and cross-phase modulation effects. Brillouin scattering is caused by the light reflecting off of acoustic phonons in the glass. This results in back-propagating light, and this can impact the transmitter as well as degrade the signal integrity as the effective loss of the effect is not stable (it is noisy). Raman scattering results from the light interacting with optical phonons, and results in energy transfer from shorter wavelength light to longer wavelength light. This extracts power from the shorter wavelength, increasing its apparent loss. This becomes important for the multi-channel/multi-system case, discussed below. Both of these effects are not sensitive to the optical phase, and so they are not dispersion dependent. However, Raman also can transfer signal modulations between both wavelengths, causing an increased electrical noise level, and this is sensitive to the signal phase, and dispersion can play an important role there. Self- and cross-phase modulations occur when the intensity of the light causes the glass index to vary, and is a manifestation of four wave mixing. This effect depends on the optical phase very much, and is usually not a major factor in access systems. The main design impact of these effects is to limit the maximum power launched into the fiber to around 10dBm per wavelength (and preferably less). As it turns out, eye safety also sets the power limits at around these same levels, so this is a good limit.

6.x.2. Extrinsic impairments

A practical optical link will have less than ideal components, and these can produce effects that reduce the performance of the link. Reflection is one such effect. Reflections commonly arise from poor connectors or splices, and also from the opto-electronic devices used in the link (mainly lasers, but also potentially detectors). The reflected light typically ends up impinging on the equipment that transmitted it, or on coexisting equipment in the same location. This can produce near-end crosstalk

(NEXT), unless the victim equipment can be protected from the reflection. The conventional way of blocking the reflections is to use an optical filter that rejects the wavelength in question (a diplexer filter).

This raises the second major imperfection of the equipment, and that is the isolation of the optical filters used in the equipment. All PON equipment use filters for diplexing and blocking filters. The blocking filters are designed to protect a receiver from unwanted other wavelength channels, e.g., far end crosstalk (FEXT). Ideal filters would be a perfect ‘brick wall’, offering high isolation immediately adjacent to the pass-band. Real filters need a guard-band spectrum to allow for the filter isolation to develop, and also to allow for filter wavelength misalignment. Older generations of PON equipment tend to have very wide guard-bands, as the state of technology and the need for upgrade were less at the time. These past design practices put limits on how much rejection can be expected from the legacy equipment.

6.x.3. Inter-channel effects

Even a simple TDM/TDMA PON has two channels operating at once, and a system that has multiple generations of equipment coexisting has many channels running. Each pair of wavelengths can have some level of interaction. One can categorize these interactions by considering the spectral separation of the two channels. If the wavelengths are far apart, so that they are outside the guard-bands of the relevant filters, then the biggest contributor to crosstalk may be Raman modulation transfer. This only happens if the channels are co-propagating, and the power levels are high. Furthermore, the power density of the Raman crosstalk is heavily weighted toward the lower frequencies (<100 MHz, typically). Analog or high-constellation QAM channels are the most affected.

If the channels are closer together, such that they are in the guard-bands of the relevant receiver, then the biggest contributor will be linear crosstalk. One has to consider how much of the offending light gets into the victim’s detector, as a ratio to the desired signal. This calculation takes into account all the losses in the interferer’s path (reflections, ODN elements, filters, etc). The sensitivity penalty produced by linear crosstalk is also influenced by the electrical spectrum of the interferer. Only the noise energy that lies inside the electrical bandwidth of the receiver is effective. Theoretical models of the crosstalk penalty (P_C) have been developed [ITU-T G.sup39].

$$Pc = -5\log\left(1 - \frac{10^{2C_L/10}}{N-1} Q^2 \left(\frac{ER+1}{ER-1}\right)^2\right),$$

where C_L is the linear crosstalk ratio in dB’s, N is the number of similar channels, Q is the signal quality factor, and ER is the extinction ratio.

$$Q = \sqrt{2}\, erfc^{-1}(2 \times BER),$$

where BER is the bit error ratio.

If the channels are very close to each other, so that their spectral difference is within the electrical bandwidth of the receiver, then coherent crosstalk can occur. This is categorically a different effect because the optical carriers now beat together to produce a strong interfering signal. This, coupled with the fact that no optical filtering can reduce the crosstalk, means that coherent crosstalk is a very powerful effect. It can be prevented by avoiding optical spectrum overlap, certainly with the main signal, but also with any inadvertent emissions that occur out of band. The coherent sensitivity penalty (P_C) has been theoretically described [ITU-T G.sup39].

$$Pc = -5\log\left(1 - 4\times 10^{Cc/10} Q^2 \frac{ER(ER+1)}{(ER-1)^2}\right),$$

Where C_C is the coherent crosstalk ratio in dB's (other variables defined as above). Note that the crosstalk factor in the exponent differs here by a factor of two when compared to the linear crosstalk factor. That is the key difference.